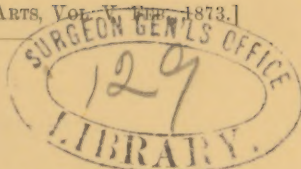


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ON THE EXPERIMENTAL DETERMINATION OF
THE RELATIVE INTENSITIES OF SOUND;

AND ON THE MEASUREMENT OF THE POWERS OF VARIOUS
SUBSTANCES TO REFLECT AND TO TRANSMIT SONO-
ROUS VIBRATIONS.

BY ALFRED M. MAYER, PH.D.,

Professor of Physics in the Stevens Institute of Technology, Hoboken, N. J.

(Read before the National Academy of Sciences, in Cambridge, Nov. 21, 1872.)

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WHILE the problems of the determination of the pitch of sounds and the explanation of timbre have received their complete elucidation at the hands of Mersenne, Young, De la Tour, König and Helmholtz, the problem of the accurate experimental determination of the relative intensities of given sonorous vibrations has never been solved.

The method I here present will, I hope, open the way to the complete solution of this difficult and important problem; and I trust that the success I have met with will instigate others, more learned and patient, to attack with superior acumen a subject which must necessarily become of fundamental importance in the future progress of acoustic research.

1. *The determination of the relative intensities of sounds of the same pitch.*

If two sonorous impulses meet in traversing an elastic medium, and if at their place of meeting the molecules of the medium remain at rest, it is evident that at this place of quiescence the two impulses must have opposite phases of vibration, and be of equal intensity.

I have, in the following manner, experimentally applied this principle to the accurate determination of the relative intensities of vibrations giving the same note, and propagated from their sources of origin in spherical waves.

Clothe two contiguous rooms with a material which does not reflect sound, and place in each room one of the sounding

bodies, and maintain these sounds of constant intensity ; or the two sources of sound may be placed in the open air, and separated from each other by a non-reflecting partition. Fix at a certain distance from each sounding body a resonator responding to its note, and attach to each resonator the same length of firm gum-tubing ; then lead these tubes to a forked pipe, so that the impulses from the two resonators meet at the confluence of the two branches of the forked tube, and connect the branch of the forked tube, in which the sounds meet, with one of König's manometric capsules. Now sound continuously one of the bodies, and the manometric flame when viewed in a revolving mirror will present its well known serrated appearance. On sounding the second body impulses from it will meet those from the first body, and if the phases of vibration of the impulses on the manometric membrane are opposed and of equal intensity, the membrane will remain at rest and the flame will now appear in the mirror as a band of light with a rectilinear upper border. But although the intensities of the pulses can easily be rendered equal by altering the distance of one of the resonators from its sounding body, yet this change of position will alter the relation of the phases of the impulses reaching the membrane, so that, if by mere chance, we get them opposed in the first position of the resonator, they will no longer be so after its change of position. But on stopping the vibrations of one of the bodies and setting it in vibration at intervals we may finally succeed in causing the impulses on reaching the membrane to have opposite phases of vibration. Such a method, which relies only on chance, can be of little value on account of its uncertainty and the tediousness of its application.

The above difficulty I have entirely removed by the following means. I cut a piece out of one of the tubes equal in length to a half-wave of the note we are experimenting on, and replace this piece of tubing with a glass tube of the same length, into which slides another glass tube also of half a wave in length. Now the experimentation becomes expeditious and certain. Sound both bodies continuously and place in a fixed position one of the resonators. Move the other to a certain distance from its sounding body and then pull out the inner glass tube until exact opposition of phase of the impulses is brought on to the manometric membrane. This condition will be known when the serrations have dropped to their minimum of elevation. If the latter do not entirely disappear from the band of light in the mirror, we must place the movable resonator at another distance and readjust the sliding tube. A few trials will give in the mirror a band of light with a straight, unruffled top border ; then we have opposed phases of vibrations at the confluence of

the branches of the forked tube, and equally intense pulses are traversing the two tubes leading from the resonators.

The distance of each resonator from its sounding body is now measured, and the inverse ratio of the squares of these distances will be the ratio of the intensities of the vibrations at the sources of the sounds, *if* the intensities of the impulses sent through a tube from a resonator varies directly with the intensities of the vibrations of the free air in the plane of the mouth of the resonator.

It will be observed that the accuracy of the determinations by this experimental method depend on three conditions. First, that the vibrating effects of the same area of a spherical sonorous wave diminish in intensity as the reciprocals of the squares of the distances of this area from the point of origin of the wave. There is every dynamic reason to believe in the truth of this proposition. The second necessary condition is that the elongation of one of the resonator tubes over the other by half a wave-length of firm glass tubing does not diminish the intensity of the impulses which have traversed it. Numerous experiments, especially those of Biot and Regnault on the aqueduct pipes of Paris, show that this short connecting tube of glass cannot in any way affect the accuracy of the measures. The third condition is that the intensities of pulses sent through a tube from a resonator vary directly with the intensities of the vibrations of the free air in the plane of the mouth of the resonator. This is a very important consideration, and as I believe there is no entirely reliable discussion of the above relation, the problem will have to be experimentally solved with the greatest care. If, however, the relations between the intensities of pulses inside the tube and those outside the mouth of the resonator shall be shown to be different (and I think they will be) from what we, for illustration, have here assumed, the process of the numerical reduction of the experiments will be only modified while the experimental method remains secure. Indeed, I cannot but consider that I have here, by applying the principle of interference, so fertile in results in optics, been the first to give an experimental method which will determine with precision the relative intensities of two sonorous vibrations producing the same note.

Savart and many other experimenters have determined the relative intensities of two sounds by placing sand or other light particles on membranes and receding from the source of sound until no motions of the particles were visible. Also Drs. Renz and Wolf (Pogg. Ann., vol. clxxiv, p. 595) give the results of experiments on the determination with the ear of the intensity of the sounds of a ticking watch. More recently Dr. Heller (Pogg. Ann., vol. ccxvii, p. 566) has made an elaborate research

on the intensities of sounds; deducing mathematically his determinations from the observed amplitudes of vibration of a membrane; and Mr. Bosanquet (L. E. and D. Phil. Mag., Nov., 1872) has just published a paper in which he proposes to measure the intensities of the sounds of pipes of different pitch by the determination of the quantity of air which each pipe consumes in sounding. But all of these experimenters acknowledge the want of precision in their measures and the difficulties in the actual practice of their methods.

When the resonators have such distances from their corresponding sounding bodies that the phases of the impulses on the membrane are opposed while their intensities are different, a residual action is given, and the intensity of this action on the membrane will depend on the relative intensities of the sources of sound and the relative distances at which the resonators are placed. It may here be interesting to consider the simplest case, that is, when the intensities of vibration at the two sources of origin of the sounds are the same, and the two resonators are placed at various distances from these points of origin, but always differ in their distances by one half wave-length. Let us call A one of the resonators, B the other. Let A be successively placed at distances from its sounding body equal to 1, 2, 3, &c., wave-lengths, and B successively at distances equal to $1\frac{1}{2}$, $2\frac{1}{2}$, $3\frac{1}{2}$, &c., wave-lengths. When the resonators are in the above positions we will suppose that the phases of vibration reaching the membrane are opposed. The following table gives the calculations made on the assumption that the intensities of the vibrations diminish as the reciprocals of the squares of their distances from the sounding bodies:

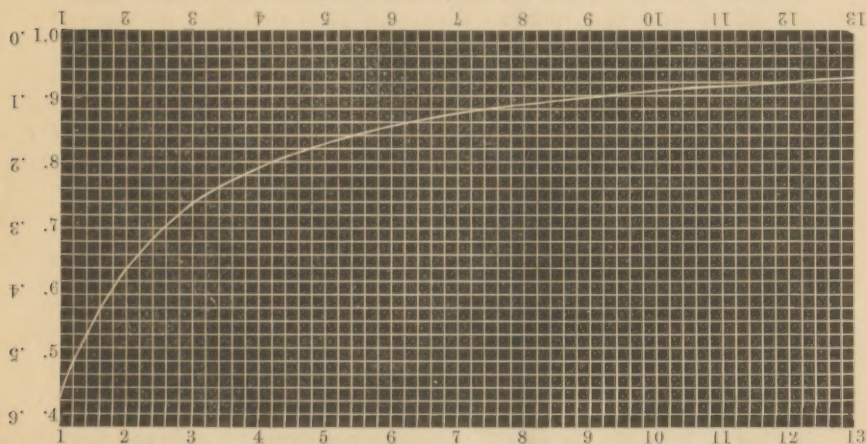
A's dist. in λ .	B's dist. in λ .	Ratios of Intensities.	Residual Effects.
1	1.5	.444	.556
2	2.5	.640	.360
3	3.5	.734	.266
4	4.5	.790	.210
5	5.5	.826	.174
6	6.5	.854	.146
7	7.5	.871	.129
8	8.5	.885	.115
9	9.5	.897	.103
10	10.5	.907	.093
11	11.5	.914	.086
12	12.5	.921	.079
13	13.5	.927	.073
24	24.5	.959	.041
25	25.5	.961	.039

We have projected these related numbers in the accompanying curve, whose abscissas represent the distances of A from

the source of sound, and whose ordinates gives the ratios of intensities between A, taken at the distances on the axis of abscissas, and B at distances from its sounding body always one half wave-length greater than A's distance from its sounding body. The formula of the curve is

$$y = \frac{x^2}{(x + \frac{1}{2})^2}.$$

If the curve be placed up side down, and referred to the corresponding numbers on the abscissas and ordinates (the latter being equal to unity minus the numbers at the corresponding points of the curve when in its first position), we have the graphical representation of the variation of the resultant intensities, contained in the fourth column of the table.



In the case of notes of different pitch, giving the same amplitude of swing to the aerial particles, the higher note will necessarily force the air to make its vibrations with a greater velocity, and the intensities will therefore not alone depend on the amplitudes of these vibrations but also on their velocities, and it has been deduced from established principles of dynamics that the apparent intensities of notes of different pitch will vary directly as the squares of the amplitudes, and inversely as the fourth power of the wave-length or periodic time. (See Mr. Bosanquet on the Relation between the Energy and Apparent Intensity of Sounds of different Pitch, L. E. & D. Phil. Mag., Nov., 1872). Hence the determination of the relative intensities of notes of different pitch becomes very complicated, and the experimental solution of the problem is encompassed with many difficulties. I however hope to be able, at some future day, to present some work in this direction when I have succeeded in

obtaining results worthy of the appellation of measures of precision.

2. *Measurement of the powers of various substances to transmit and to reflect sonorous vibrations.**

After we have succeeded in obtaining a measure of the intensity of the vibrations of the air at a certain distance from the sounding body, we can measure the powers of various substances to transmit, absorb and reflect sonorous vibrations.

To accomplish this I place one of the sounding bodies in the focus of a parabolic reflector and bring the two resonators at such distances from their sounding bodies that the intensities of the pulses traversing their respective tubes are equal. We then place in front of, but not too near, the mouth of the resonator, in front of the reflector, the plane surface of the substance

* In the Smithsonian Report for 1857 will be found an account of very interesting and valuable experiments, by Prof. Joseph Henry, bearing on "Acoustics applied to Public Buildings." In these investigations, Prof. Henry determined the *relative* powers of various substances to reflect, transmit and absorb sonorous vibrations by placing on the bodies the foot of a tuning-fork, and comparing the duration of its sound when thus placed with that given when the fork was suspended in the free air by a fine cambric thread. Thus suspended the fork vibrated during 252 seconds. Placed on a large, thin pine board, its vibrations lasted about 10 seconds. In this case "the shortness of duration was compensated for by the greater intensity of effect produced." The fork having been placed successively on a marble slab, a solid brick wall, and on a wall of lath and plaster, its vibrations lasted respectively 115 seconds, 88 seconds, and 18 seconds.

Placed on a cube of india-rubber, the sound emitted by the fork was scarcely greater than when it was suspended from the cambric thread, but its *duration* was only 40 seconds. Here Henry puts the question, what became of the impulses lost by the tuning-fork? They were neither transmitted through the india-rubber nor given off to the air in the form of sounds; but were probably expended in producing a change in the matter of the india-rubber, or were converted into heat, or both. Though the inquiry did not fall strictly within the line of this series of investigations, yet it was of so interesting a character in a physical point of view to determine whether heat was actually produced, that the following experiment was made. * * * The point of a compound wire formed of copper and iron was thrust into the substance of the rubber, while the other ends of the wire were connected with a delicate galvanometer. The needle was suffered to come to rest, the tuning-fork was then vibrated, and its impulses transmitted to the rubber. A very perceptible increase of temperature was the result. The needle moved through an arc of from one to two and a half degrees. The experiment was varied, and many times repeated; the motions of the needle were always in the same direction, namely, in that which was produced when the point of the compound wire was heated by momentary contact with the fingers." We have pleasure in again calling attention to this most beautiful experiment of Prof. Henry, for he was, I believe, the first to obtain the production of heat on the *absorption* (so to speak) of sonorous vibrations; and although several experimenters have subsequently obtained the same results, not one of them gives Henry credit for antecedent work. In 1868 I published a full account of the above experiment in my *Lecture, Notes on Physics*, p. 79. Van Nostrand, N. Y.

In the same paper Professor Henry obtained a few qualitative relations in the reflecting powers of various substances, by placing a watch between the centre and focus of a concave mirror; he then receded along the axis of the diverging sonorous beam, with a hearing trumpet. Paper and flannel were now stretched between the watch and the mirror, and the intensity of the sound was found to be diminished by the reflecting and absorbing powers of these substances.

whose transmitting and reflecting powers we would determine. Serrations now appear in the flame, because part of the force of the pulses which previously sounded the resonator are now reflected from the interposed substance. The resonator which has not the reflecting surface in front of it is now gradually drawn away from its sounding body, and at each successive point of remove the pulses propagated through the two resonator tubes are brought to opposition of phase on reaching the membrane by means of the glass telescoping tube. Equality of impulses having been obtained, we measure the distance of the resonator, which has not the reflecting substance in front of it, from the origin of its sounding body, and this measure, together with the known previous distance of this resonator, when equality was attained before the interposition of the reflecting surface, gives the data for the computation of the intensity of the *transmitted* vibration. This number subtracted from the measure of the intensity when the substance was not before the resonator, taken as unity, gives the reflecting power of the substance plus its absorbing power.

It is very important, in such measures, to be sure that a plane wave surface is reflected from the mirror. This character of wave can be approximately obtained by placing the mouth of a closed organ-pipe at or very near the principle focus of the mirror and testing, by the method we have described above, the equality of intensity of the vibrating air in front of the mirror as we recede along its axis. We thus, by trial, at last succeed in obtaining a sufficiently plane wave-surface. Care must also be taken that the surface of the reflecting substance is so large that no inflected vibrations can act on the resonator.

I have made several measures of intensity and of transmitting and reflecting powers, but as the experiments were made in a room whose walls, ceiling and floor gave reflected sonorous waves, I will not present measures until I have arranged suitable apartments for their accurate execution.

November 13th, 1872.

